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STRUCTURING OF COLLISIONLESS, HIGH VELOCITY ION CLOUDS

Introduction

In recent years there have been a number of releases of barium ion clouds at very high altitudes with high velocities perpendicular to the geomagnetic field. A number of examples include: the NASA-MPE 5 R_E barium release,^{1,2} the Avefria barium jet,³ the NASA-CAMEO experiment,⁴ and the University of Alaska radial shaped charge.⁵ It is the purpose of this note to show that these clouds should be unstable to a Rayleigh-Taylor instability driven by the deceleration of the cloud in the geomagnetic field. This Rayleigh-Taylor instability could cause a very rapid striation of the ion clouds.

Instability Theory

We consider the ion continuity equation,

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \underline{v}_i) = 0 \quad (1)$$

and conservation of electric current,

$$\nabla \cdot \underline{J} = 0. \quad (2)$$

Define $C = \int \frac{\rho_i}{B^2} d\ell$ the capacitance of the ion cloud integrated along the magnetic field. Then the field line integrated equation (1) can be written

$$\frac{\partial C}{\partial t} + \nabla \cdot (C \underline{v}_{i\perp}) = 0. \quad (3)$$

For a cold collisionless plasma the field line integrated momentum equation yields

$$\underline{J} = C \frac{\partial \underline{E}}{\partial t}. \quad (4)$$

The electric current is strictly a polarization current which when substituted into equation (2) results in

$$\nabla \cdot C \frac{\partial E}{\partial t} = 0. \quad (5)$$

We now take $C = C_0 + C^1 \exp - i(\omega t - kx)$ and $E = E_0 + E^1 \exp - i(\omega t - kx)$ where $E_0 = v_0 \times B$ and v_0 is the initial cloud velocity. Linearizing (3) and (5) we obtain

$$- i \omega C^1 + \frac{E^1}{B} \frac{C_0}{L} = 0 \quad (6)$$

and

$$i k C^1 \frac{\partial E_0}{\partial t} + \omega k C_0 E^1 \quad (7)$$

where

$$1/L = \frac{1}{C_0} \frac{dC_0}{dy}. \quad (7)$$

Solving (6) and (7) for ω yields

$$\omega^2 = - \frac{1}{BL} \frac{\partial E_0}{\partial t}$$

which gives the growth rate for the Rayleigh-Taylor instability

$$\gamma = \sqrt{- \frac{1}{L} \frac{\partial v_0}{\partial t}}. \quad (9)$$

We see that the cloud is unstable on its leading edge for deceleration. If $\partial v_0 / \partial t$ is large enough and L small enough very large growth rates are possible.

Deceleration of Ion Clouds

For many high velocity ion clouds the deceleration will occur via line-tying forces in the ionosphere. In this case we can easily estimate the rate of deceleration. The cloud causes polarization currents which are closed in the ionosphere via a Pederson current. That is,

$$C \frac{\partial E}{\partial t} = - \Sigma_p E. \quad (10)$$

Equation (10) has solution

$$E = E_0 \exp - (\Sigma_p/C)t \quad (11)$$

The velocity has the same solution as equation (11), therefore we may write the deceleration as

$$\frac{\partial V}{\partial t} = - V_0 \frac{\Sigma_p}{C} \exp - (\Sigma_p/C)t \quad (12)$$

where V_0 is the initial cloud velocity, Σ_p is the ionospheric Pederson conductance, and C is the capacitance of the plasma cloud. Choosing $C = 5$ farads, $\Sigma_p = 5$ mhos, reasonable values for a moderate size barium cloud and a twilight ionosphere, gives for the deceleration

$$\frac{\partial V}{\partial t} = - 1.0 V_0 \exp(-t). \quad (13)$$

If now $V_0 \sim 10 \text{ km sec}^{-1}$ and $L \sim 1 \text{ km}$ we find $\gamma \approx 2.5 \text{ sec}^{-1}$ at a time of 0.5 seconds. Earlier, of course, the growth rate would be larger. For $L \sim 100$ meters, $\gamma \approx 8 \text{ sec}^{-1}$; and for $L \sim 10$ meters, $\gamma \approx 25 \text{ sec}^{-1}$. This computation shows that the growth of the instability and cloud striation would be considerable in a few seconds. Another more complicated analysis of the cloud deceleration by Alfvén waves⁶ also leads to similarly large growth rates.

Conclusions

In the preceding paragraphs, we have shown that cold, collisionless, high velocity ion clouds are unstable to the "Rayleigh-Taylor" instability in the ionosphere and magnetosphere. We have also demonstrated for one example that the instability growth time can be much less than 10 seconds.

The instability we have described is another member of a large class of "interchange instabilities" which includes the well-known "gradient drift" and "gravitational Rayleigh-Taylor" instabilities.⁷ In view of this instability's rapid growth and its close relationship to other well-known ion cloud structuring instabilities, it would appear to be a most likely candidate for generating the rapid structuring which has been observed in collisionless, high velocity ion cloud experiments.

This instability would also be pertinent to rapid structure growth in the coupling shell of nuclear detonations.

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